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PATENT APPLICATION
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PHASE ARRAY OXIDE-CONFINED VCSELS

BACKGROUND

The relative ease with which vertical cavity surface-emitting lasers (VCSELs) can be fabricated has resulted in the increasing use of VCSELs in a variety of applications such as printing, data storage and network communications. However, the small light emission area of each VCSEL severely limits the light output power that can be generated and output by each VCSEL. This shortcoming is especially severe in single mode devices. The narrow beam profile of single mode devices is highly desirable in a range of applications ranging from printing to wide area network communications.

One method of increasing the optic power at a target point is to align and simultaneously switch several lasers to form a composite beam. However, using an array of independent lasers results in each laser having its own independent intensity pattern. Combining independent intensity patterns results in a composite beam that appears as several distinct spots. These distinct spots are unsuitable for communications and printing applications where a central radiation lobe with a high concentration of power output is desired.

Thus an improved method of combining the output of an array of lasers, preferably VCSELs, to generate a single spot composite beam is needed.

SUMMARY OF THE INVENTION

The present invention relates generally to the field of laser fabrication. More particularly, a plurality of VCSELs are fabricated. A first VCSEL is at least partially surrounded by a first oxide wall and a second VCSEL is at least partially surrounded by a second oxide wall. A contact is structured to simultaneously provide power to both the first VCSEL and the second VCSEL. In one embodiment of the invention, a high gain coupling region couples the active region of the first VCSEL to the active region of the second VCSEL through a gap in the first oxide wall and a corresponding gap in the second oxide wall. The high gain coupling region enhances mode coupling between the first VCSEL and the second VCSEL.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete appreciation of the invention may be more readily understood by referring to the detailed description and the accompanying drawings.

Fig. 1 shows a side view of an etched pillar laterally-oxidized VCSEL structure.

Fig. 2 shows a top view optical micrograph of oxidized VCSEL units used in a phase array.

Fig. 3 shows a schematic implementation of an 8x8 laterally-oxidized phase array.

Fig. 4 is a flow chart that describes one method of forming a laterally-oxidized VCSEL phase array.

Fig. 5 is a graph that plots the light output of a VCSEL phase array versus an input current.

Fig. 6 shows an 8x8 VCSEL phase array design where adjacent via holes from the verticies of a square.

Fig. 7 shows an 8x8 VCSEL phase array design where adjacent via holes form the verticies of a triangle.

Fig 8 shows a VCSEL phase array design where the extent of oxidation has been reduced to allow high gain coupling regions between adjacent laser apertures.

DETAILED DESCRIPTION

In the following detailed description, a method and system of forming an array of VCSELs using laterally oxidized apertures will be described. A common contact addresses several VCSELs simultaneously. In one embodiment of the invention, the VCSELs will be closely spaced and separated by thin, laterally oxidized regions designed to promote mode leakage between adjacent VCSELs. The mode leakage keeps the output of adjacent VCSELs in phase thereby allowing the output of these adjacent VCSELs to be combined into a coherent composite beam.

Figure 1 shows a cross-sectional side view of an oxide-confined VCSEL mesa-structure with an etched pillar structure. Mesa sidewalls 104 provide access to buried aluminum-containing layers 108. Buried layer 108 is selectively oxidized to form laser apertures 112, 116, 120. In typical prior art VCSELs, the edge of the mesa completely surrounds the laser aperture such that an air gap 124 completely separates adjacent laser apertures 112 and 116. The air gap prevents close coupling of optical fields between adjacent lasers.

Using via holes instead of pillars to access the oxidation layers allows much tighter packing of VCSEL structures. U.S. Patent 5,978,408 by Robert Thornton and entitled "Highly Compact Vertical Cavity Surface Emitting Lasers" issued November 2, 1999 and hereby incorporated by reference in its entirety, describes

using via holes to access the oxidation layers. The via holes are typically arranged along the corners of a polygon such that upon oxidation, the oxidation fronts originating from each via hole expands and merges with oxidation fronts from adjacent via holes to define a laser aperture at the center of the polygon.

Figure 2 shows a top view micrograph of four laser apertures 204, 208, 212, 216. By packing closely adjacent laser apertures and minimizing the material between adjacent laser apertures, high inter-element coupling of the optical output of each VCSEL can be achieved. In order minimize the oxidation layer separating adjacent lasers, the oxidation process is typically terminated before each aperture is completely surrounded by oxidized material.

Figure 3 illustrates adjacent laser aperture regions such as region 304, 308 that share different sections of an oxidation front generated by a common via hole 312. Sharing the oxidation front generated by each via hole increases VCSEL density in a unit area and further enhances mode coupling between neighboring VCSELs. Ideally, sufficient mode coupling induces mode locking between adjacent aperture regions. Figure 3 shows a 64 VCSEL element structure arranged in an 8x8 rectangular array. In the illustrated embodiment, a transparent indium tin oxide (ITO) electrode 316 covers the entire array. Contacts 320 couple the ITO electrode to a power supply (not shown). The ITO electrode provides an injection current to the laser apertures.

An oxidized material at least partially surrounds each VCSEL in the array. The oxidized material forms a lateral waveguide defining an optical aperture.

Limiting the extent of lateral oxidation enhances mode leakage and coupling between adjacent VCSEL laser apertures. For example, assuming an eight micrometer straight line distance between adjacent via holes in the hexagonal structure of Figure 3 , the oxidation extent 314, defined to be the shortest distance from the edge of the via hole to the edge of the oxidation, should preferably be less than 0.5 micrometers. To achieve a 0.5 micrometer oxidation front, a typical oxidation time for $Al_{0.8}Ga_{0.2}As$ is approximately 7 minutes.

The actual spacing between adjacent oxidation fronts defining a laser aperture varies according to a number of factors including the wavelength output by the laser and the effective refractive index within the aperture. In particular, the extent of the evanescent wave that induces mode locking determines the spacing of via holes and the oxidation times. The electromagnetic field strength of an evanescent wave typically decreases as a function of $e^{-z/zo}$ where z is the distance from the boundary of the aperture and zo is a characteristic length. This characteristic length is approximately equal to the wavelength of the laser divided by 2pi(sqrt(2(n*f*dn))) where n is the effective refractive index of the aperture, f is the fraction of the oxidized to unoxidized area in the coupling region between array elements, and dn is the effective refractive reduction in the oxidized region. detailed computations are provided in an article entitled "Effective index model for vertical-cavity surface-emitting lasers" by G.R. Hadley in Optic Letters, vol. 20, no. 13 pp 1483-1485, 1995 which is hereby incorporated by reference.

A typical VCSEL operates around 850 nm, the effective index of refraction n is approximately 3, and an example effective refractive reduction dn is approximately 0.065. Assuming the structure of Figure 3 has a lateral oxidation extent of 0.5 micrometers, the characteristic length z_o is approximately 0.87 micrometers. Based on such approximations, a mode interaction length may be computed. The mode interaction length is typically assumed to be approximately five times the characteristic length. However, the mode interaction length may be extended up to approximately ten times the characteristic length by further distancing the oxidation epitaxial layer 150 of Figure 1 further from the laser active regions 154. Using such parameters, the laser dimensions are adjusted to allow for mode locking between adjacent lasers.

A laser phase array usually operates in higher order supermodes producing two or more radiation lobes existing in the far field. However, single mode operation that concentrates light power in a single radiation lobe is desirable for many applications. In order to achieve single mode operation, one embodiment of the invention blocks or otherwise diminishes the unwanted far field lobes. An alternative embodiment of the invention achieves fundamental supermode operation (with a single radiation lobe in the far field region) by positioning high gain coupling regions between adjacent laser apertures. These high gain coupling regions may have higher gains than the gain found in the actual laser aperture. One method of increasing gain is to increase the conductivity of the coupling regions compared to the conductivity of

the laser aperture regions. Higher conductivity increases the current density (more current per unit area) in the high gain coupling regions compared to the laser aperture regions.

One method of increasing the conductivity is to dope the high gain coupling region with a suitable dopant such as zinc. The doping may be done by masking the laser aperture regions and diffusing a suitable dopant into the coupling region. Alternatively, the dopant may be added by direct ion implantation.

It is undesirable for the doped high gain region to emit laser light. In order to prevent lasing in the high gain coupling region, the mirror reflectivity over the coupling region may be reduced. This reduction can be accomplished by, for example, eliminating part or all of the upper mirror layers above the coupling region. In practice, VCSEL wafers can be masked so that upper DBR mirrors in unprotected areas above the coupling region can be selectively etched by, for example, chemically-assisted ion beam etching.

A second method of reducing reflectivity of mirrors above the high gain coupling region is to deposit additional thin film layers on that region. These additional layers reduce reflectivity if they are not specifically designed to phase match the existing mirror layers. Efficient reflectivity reduction occurs when the additional layers are specifically designed as anti-reflection coatings to negate the reflectivity of the DBR layers. Well known anti-reflection design techniques are

taught in textbooks such as "Optics" by Hecht and Zajac, 1973, chapter 9.9 which is hereby incorporated by reference.

Still a third method of preventing lasing in the high gain coupling region is to selectively introduce optical loss either in the coupling region itself or in the mirrors above the coupling region. For example, heavy p-type doping in the mirror layers, near the active light-emitting layers enhances free carrier absorption. The higher optical loss decreases cavity quality factor and increases the threshold for lasing in those areas.

Figure 4 is a flow chart that describes one method of fabricating a VCSEL laser phase array. In block 404, a VCSEL epi-structure is grown. An example structure typically includes an n-doped DBR (distributed Bragg reflector stack) followed by an active layer and a p-doped DBR on a substrate. The active layer allows selective oxidation, typically by including a high Al-content in the active layer regions to be oxidized.

Block 408 describes forming high gain coupling regions between apertures. Formation of these coupling regions encourages fundamental supermode operation. As previously described, one method of forming the high gain coupling region includes diffusing a p-dopant such as zinc to increase the conductivity of the coupling region. Masks overlaying the laser aperture controls diffusion of the p-dopant into the coupling region. In one embodiment of the invention, these same masks may be used to allow selective etching of the mirrors above the high gain

coupling region as described in block 410. The selective etching reduces mirror reflectivity and prevent lasing in the coupling regions. After use, the masks may be removed.

In block 412, a transparent electrode is deposited over the wafer surface. In one embodiment of the invention, a sputtering process is used to deposit indium tin oxide (ITO) or Zinc Oxide to form a transparent electrode. The transparent electrode simultaneously provides current to several adjacent lasers in the laser array. The transparent electrode may also overlay the high gain coupling regions to provide current, and thus optical gain, into the coupling regions. In one embodiment of the invention, the transparent electrode forms a "blanket" over the entire laser array uniformly injecting current while simultaneously allowing high light output through the transparent electrode. Adjusting the thickness of the transparent electrode to one half the wavelength of light output by the laser array minimizes light reflections by the electrode. After transparent electrode deposition, successive rapid anneals may be performed. A first anneal crystallizes the sputtered transparent electrode material. A second anneal forms an ohmic contact between the transparent electrode and the underlying GaAs material.

After deposition of the transparent electrode, a lattice of via holes are patterned. In block 416, via holes are etched. In one embodiment, a dry etch is used to etch through the transparent electrode and the underlying epi layers exposing the buried oxidizable layer, typically a high aluminum content AlGaAs layer near the

active region. The via holes are arranged such that each set of via holes form the verticies of a polygon surrounding each laser aperture.

In order to form oxidized waveguides, the laser array is placed in a wet oxidation furnace to laterally oxidize the buried layer through the via holes as described in block 420. The time and temperature of the oxidation process depends on the oxidation extent. Limiting the oxidation time prevents an oxidation region originating from a via hole from contacting an adjacent oxidation region originating from an adjacent via hole. The unoxidized region remaining between adjacent oxidized regions serves as the high gain coupling regions between adjacent laser apertures. The oxidation regions form the lateral waveguide array.

In block 424, metal contacts are attached. These metal contacts couple the transparent electrode to a power source. In block 428, ion implantation creates insulating regions between adjacent sub-units. Each sub-unit serves as an independently addressable set of phase array lasers. The ion implantation may use a variety of elements such as hydrogen.

In block 432, a second electrode is attached to the phase array of lasers. In one embodiment of the invention, the second electrode is an n-contact metal deposited on the wafer backside.

Figure 5 shows a room temperature CW light output versus input current curve of a typical 64 element array of VCSELs. Proper heat sinking of the

VCSEL array allows generation of significantly higher light output levels at a given current level.

Although Figure 3 shows a laterally oxidized 8x8 VCSEL phase array structure formed using a hexagonal arrangements of via holes, Alternative arrangements may be used. Figure 6 shows a higher density of VCSELs formed by using a square or grid arrangement of via holes. Each set of four via holes such as via holes 604, 608, 612, 616 form the verticies of a square polygon that surrounds laser aperture 620. A laterally oxidized region, such as laterally oxidized region 624, surrounds each via hole such as via hole 604. The oxidized region forms the edge of the waveguide surrounding laser aperture 620. Typically, the laterally oxidized regions are made small in extent such that a gap or coupling region 628 exists between adjacent laterally oxidized regions. The coupling region allows mode coupling between adjacent laser apertures such as laser aperture 620 and laser aperture 632.

Figure 7 shows an alternative, compact arrangement of a laterally oxidized 8x8 VCSEL phase array design that utilizes a triangular device geometry. In Figure 7, three via holes, such as via holes 704, 708, 712 form the verticies of a triangle polygon that surrounds a corresponding laser aperture such as laser aperture 716. A laterally oxidized region, such as oxidized region 720 surrounds each via hole. As in the structure of Figure 6, the laterally oxidized regions form a waveguide for each laser aperture. In the embodiment of Figure 7, adjacent oxidized regions

contact, for example oxidized region 820 contacts oxidized region 824, resulting in reduced mode coupling between adjacent laser apertures.

Figure 8 shows a structure similar to the structure of Figure 7 except that high gain regions such as high gain region 828 separate adjacent oxidized regions, such as oxidized regions 820 and 824. Thus in the structure of Figure 8, each oxidized region includes only one corresponding via hole such that high gain regions and laser apertures completely surround each oxidized region. In other words, an oxidized region originating from a first via hole does not contact an adjacent oxidized region originating from an adjacent via hole. The high gain region, such as high gain region 828, couples adjacent laser apertures and allows significant mode coupling between adjacent laser apertures, such as laser apertures 832 and 836.

Although a number of details and examples of various structures have been provided, it should be understood that the foregoing description is intended to be illustrative of the invention. Variations and modification of the descriptions provided herein will present themselves to those skilled in the art. For example, the provided detailed description has identified example dimensions, particular VCSEL structures, materials used, oxidation extents, and time periods used in fabrication. However, other methods, other materials and different oxidation extents may also be used. Accordingly, the present description should not be read as limiting the scope of the invention except as described in the claims that follow.